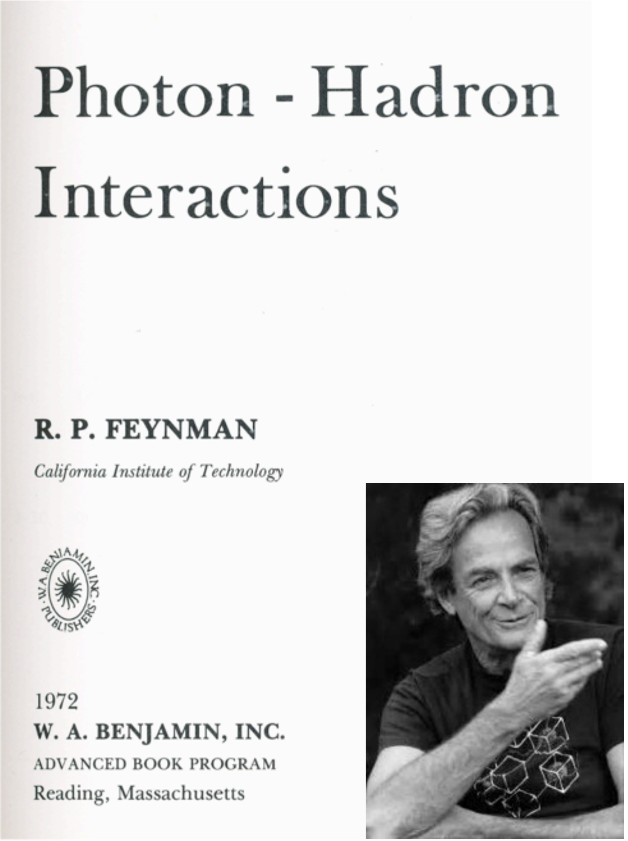
VIRTUAL PHOTON RADIATION FORM DENSE QCD MATTER

Joachim Stroth, Goethe University / GSI

EMMI RRTF: The physics of neutron star mergers at GSI/FAIR

June 4-15, 2018



Photon - Hadron Interactions

R. P. FEYNMAN

California Institute of Technology

W. A. BENJAMIN, INC. PUBLISHERS

1972

W. A. BENJAMIN, INC.

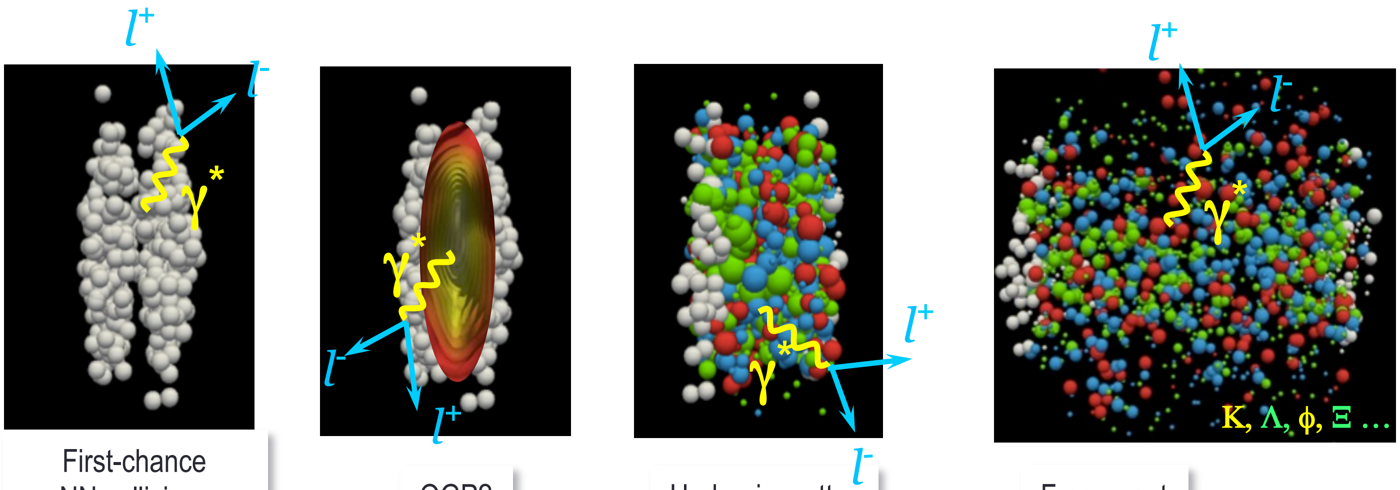
ADVANCED BOOK PROGRAM

Reading, Massachusetts

Program

- Thermal dilepton emission rates
- Establishing a „standard candle“
- Results for thermal radiation
- Other supporting observables
- Conclusion

Courses of the Heavy-Ion Collision



First-chance NN collisions or parton collisions

QGP?

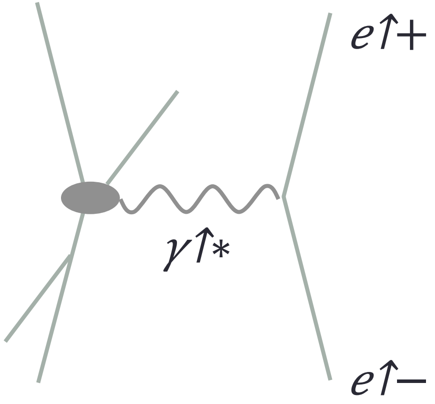
Hadronic matter

Freeze-out

τ ~1 – 30 fm/c
(~10^{-23} s)

Time-like photons radiated from a hadronic/partonic system

$$E_+ E_- \frac{dP}{d^3p_+ \, d^3p_-} \propto L^{\mu\nu}(q) \frac{1}{q^4} \Pi_{\mu\nu}(q)$$



$$M^2 = q^2 = (p_+ + p_-)^2$$

At not so high temperatures the dominant elementary processes are:

- pp, np Bremsstrahlung
- Baryon-Dalitz decays
- $\pi-\pi$ annihilation
- qq annihilation

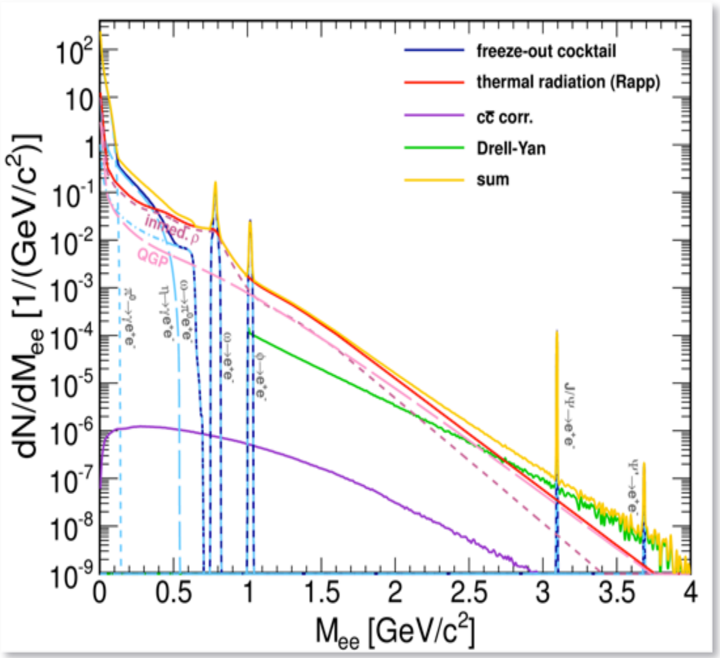
Meson-Dalitz and vector rmeson decays are considered „background" since they mostly decay after freeze-out

Theoretical Approaches to Medium Radiation

Medium radiation from *Thermal Emission Rates* (ϵ):

$$\frac{d^4 N}{dM\,dy\,dp_t\,d\alpha} = \int \frac{\alpha^2}{\pi^3 M^2}\, f_B\,(q_0 \ldots$$

$$\equiv \int \frac{d^4 \epsilon}{dq}\,[T(\boldsymbol{x}),\mu_B(\boldsymbol{x}),v(\boldsymbol{x})]\, d\boldsymbol{x}$$



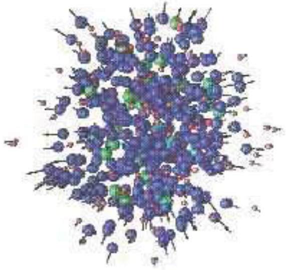
shining

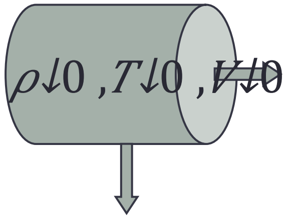
coarse graining

or

isentropic expansion

UrQMD





Dilepton emission from *Microscopic Transport.*

See also: Ralf Rapp arXiv-1110-4345

Vector Meson Dominance in Hot & Dense Matter

Generalized „Bremsstrahlung" – Fourier transform of current-current correlation function $\langle j(x), j(0) \rangle$:

$$\Pi_{EM}^{\mu\nu}(q) = \int d^4x\, e^{iqx}\, \Theta(x_0) \langle [j_{EM}^{\mu}(x), j_{EM}^{\nu}(0)] \rangle_T$$

L. McLerran, K. Toimela, Phys. Rev. D31 (1985)

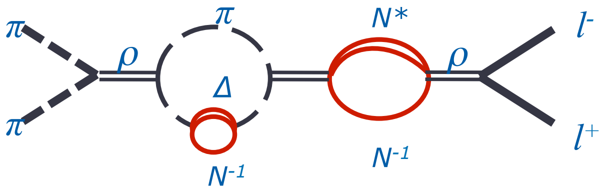
Extension of the Gounaris-Sakurai formula to a thermal pion gas: *C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65*

$$j_{EM}^{\mu} = \frac{1}{2}(\bar u \gamma^{\mu} u - \bar d \gamma^{\mu} d) + \frac{1}{6}(\bar u \gamma^{\mu} u + \bar d \gamma^{\mu} d) - \frac{1}{3}\bar s \gamma^{\mu} s = \frac{1}{\sqrt{2}} j_{\rho}^{\mu} +$$

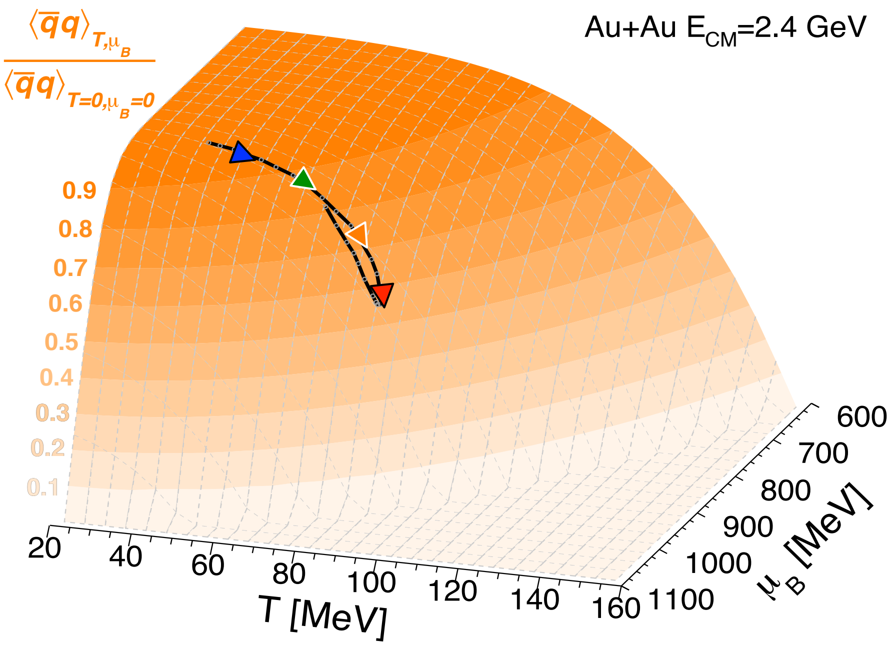
Hadronic current can be approximated by the imaginary part of the in-medium ρ propagator.
Inclusion of meson-baryon coupling, ρ only:

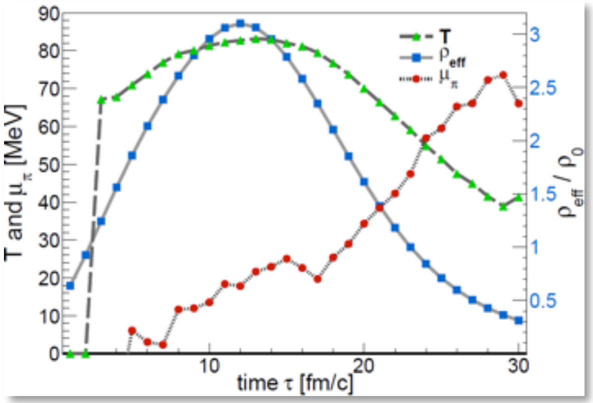
$$\mathrm{Im}\Pi_{EM}^{med.}(M) = (m_{\rho}^2 / g_{\rho})^2\, \mathrm{Im} D_{\rho}(M, q; \mu_B, T) \qquad D_{\rho}(M, q; \mu_B, T) = 1/(M^2 - m_{\rho}^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M}$$

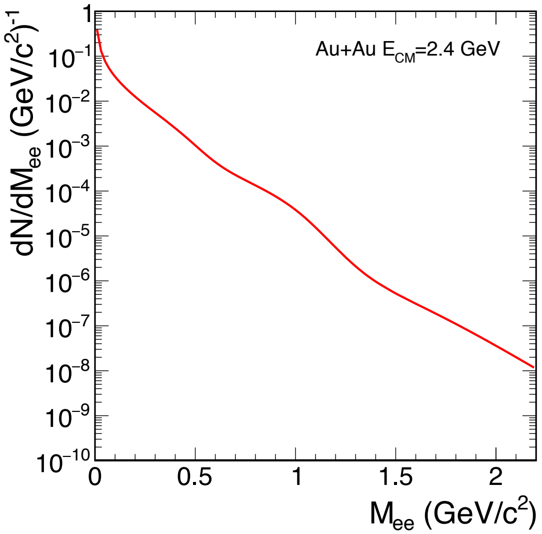
R. Rapp, J. Wambach: Adv.Nucl.Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496



The SIS18 energy regime (HADES)





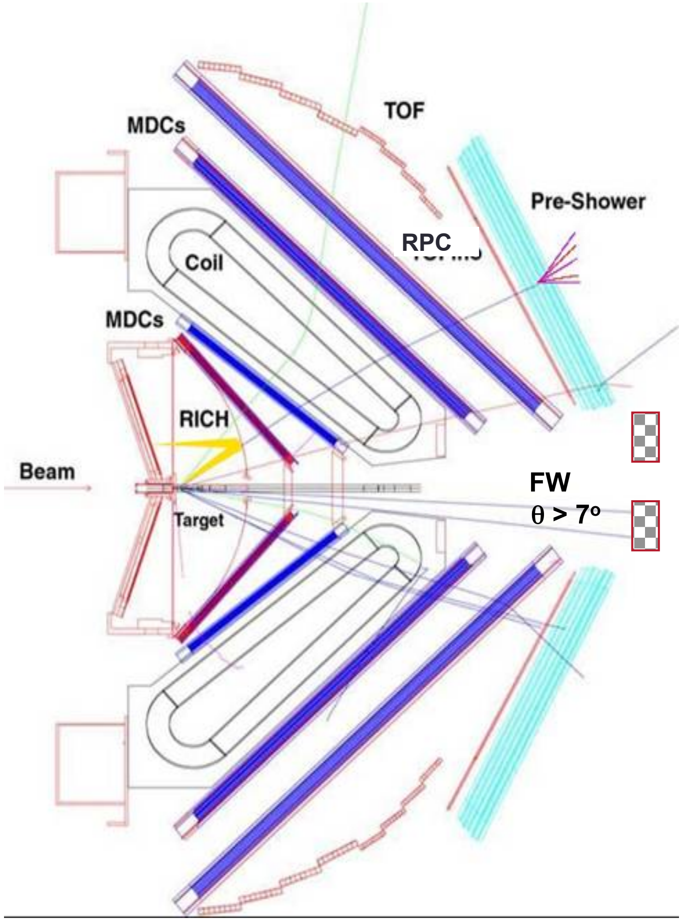


T. Galatyuk, F. Seck, R. Rapp, J. Stroth, Eur. Phys. J. A 52 (2016) 131

The HADES Spectrometer

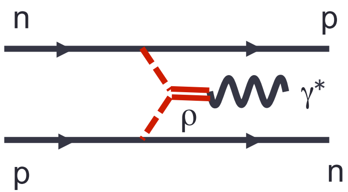
- High Acceptance Di-Electron Spectrometer
  - Designed in the nineties to measure the in-medium ρ mass-shift in 1A GeV Au+Au collisions.
  - combines aspects of hadron physics with (ultra-) relativistic heavy-ion physics.

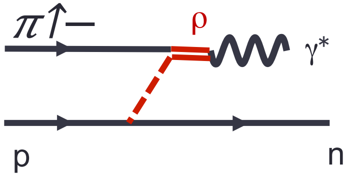
- Detector design
  - Toroidal spectrometer with six-sector superconducting magnet (field integral: 0.3 - 0.15 Tm)
  - Low-mass tracking with drift chambers
  - RICH surrounding the target in field-free region. CsJ photon detector now replaced by MAPMTs.
  - RPC and scintillator based time-of-flight systems
  - Electromagnetic Shower Detector. Now replaced by ECAL based on lead glass.
  - Various complementary detector systems (FW, Cerberus, T0)

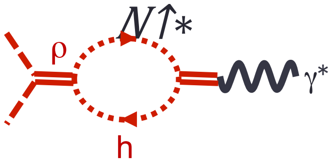


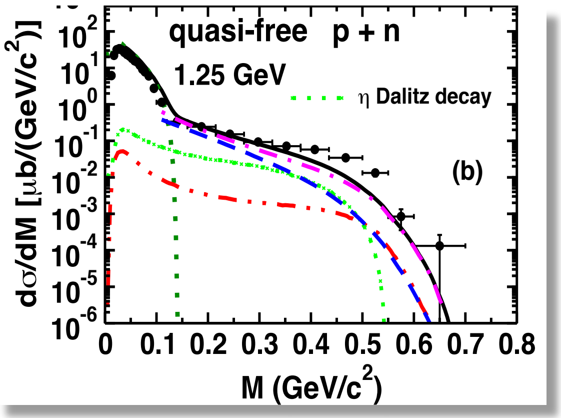
The role of virtual pions in dilepton production

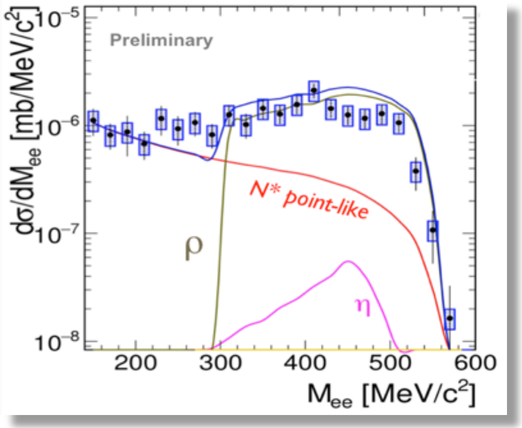
- HADES results for different collision energies.
- Dilepton production involves virtual pions (cloud of baryons)

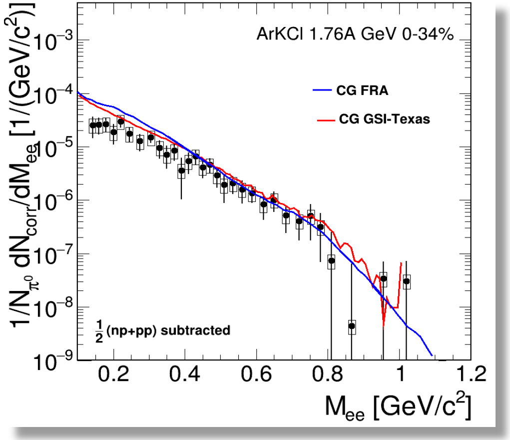




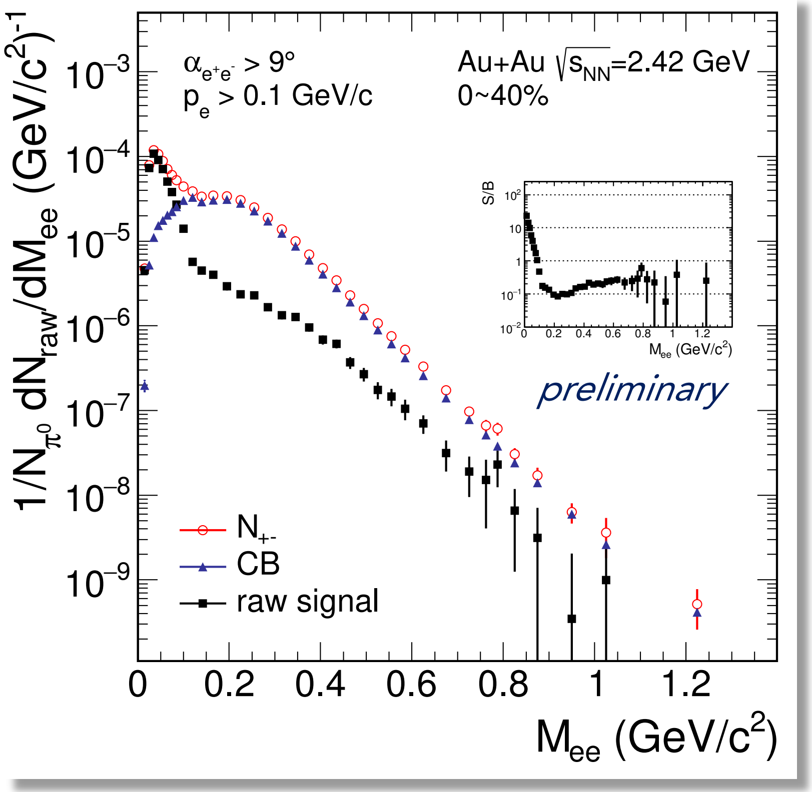


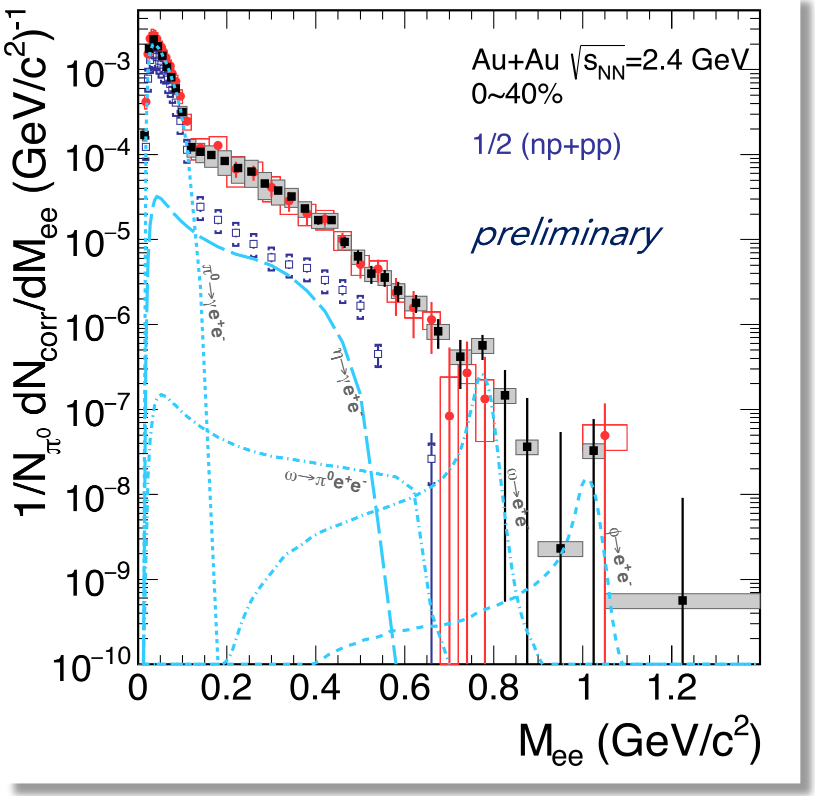




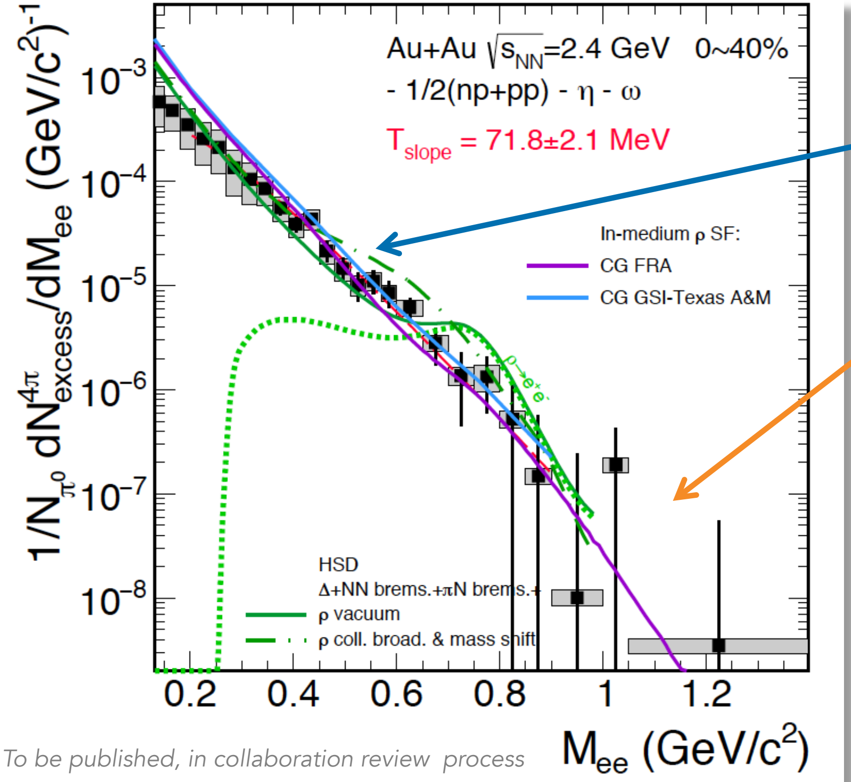


Inclusive Dielectron Yields from $Au+Au\ (\sqrt{s}=2.4\ AGeV)$





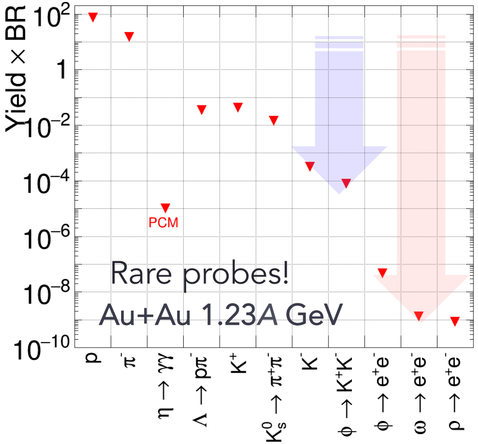
Thermal Dileptons from HADES Au+Au 1.23*A* GeV



To be published, in collaboration review process

0.3 < M < 0.7 GeV:
- In-medium spect. funct.
- fireball life time
- fireball temperature(1)

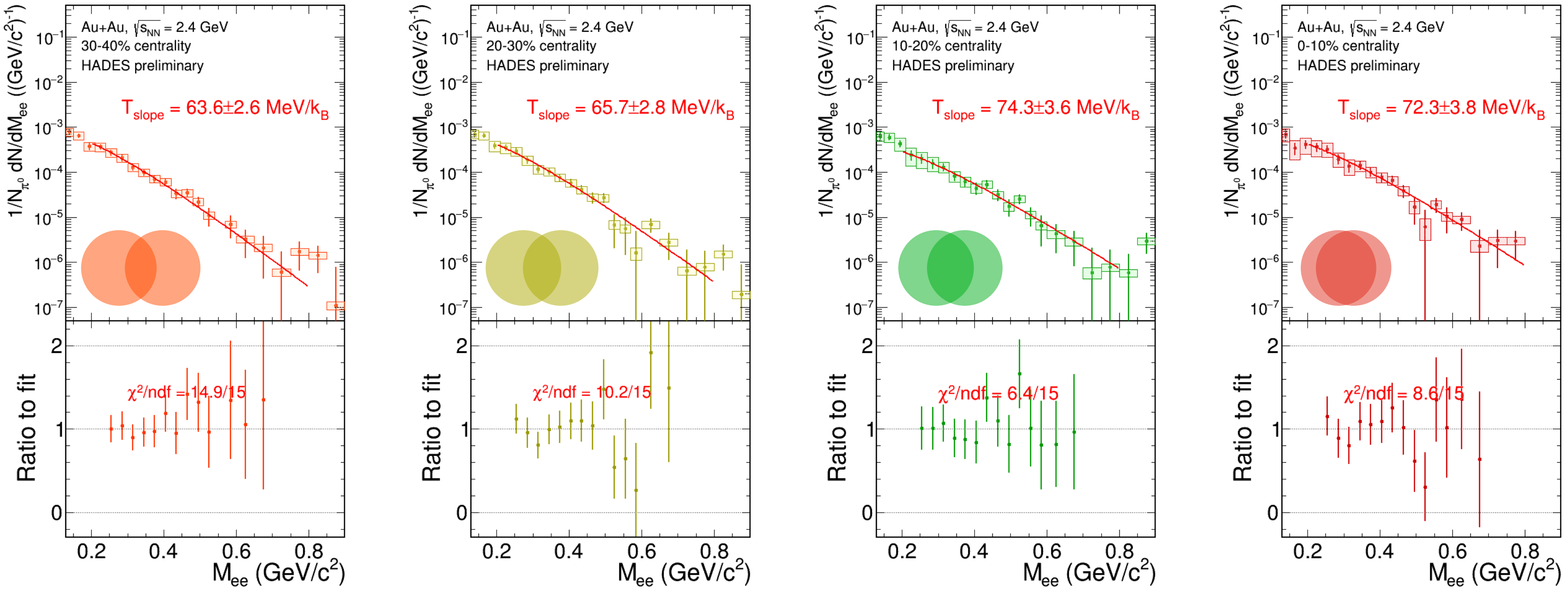
M > 1 GeV/c²:
- ρ – a1 chiral mixing
- dominated by contribution from the hottest and densest region



- Microscopic transport(2):
  - vacuum ρ spectral function and Δ regeneration
  - & explicit broadening and density dependent mass shift
- Coarse-grained UrQMD(3)
  - thermal emissivity with in-medium propagator (4)
  - $\rho - a_1$ chiral mixing(5) (not measured so far)

(4) Rapp, van Hees; arXiv:1411.4612v
(2) E. Bratkovskaya;
(3) CG FRA Endres, van Hees, Bleicher; arXiv:1505.06131
CG GSI-TAMU; Galatyuk, Seck, et al. arXiv:1512.08688
(4) Rapp, Wambach, van Hees; arXiv:0901.3289
(5) Rapp, Hohler; arXiv:1311.2921v

Excess radiation in centrality bins

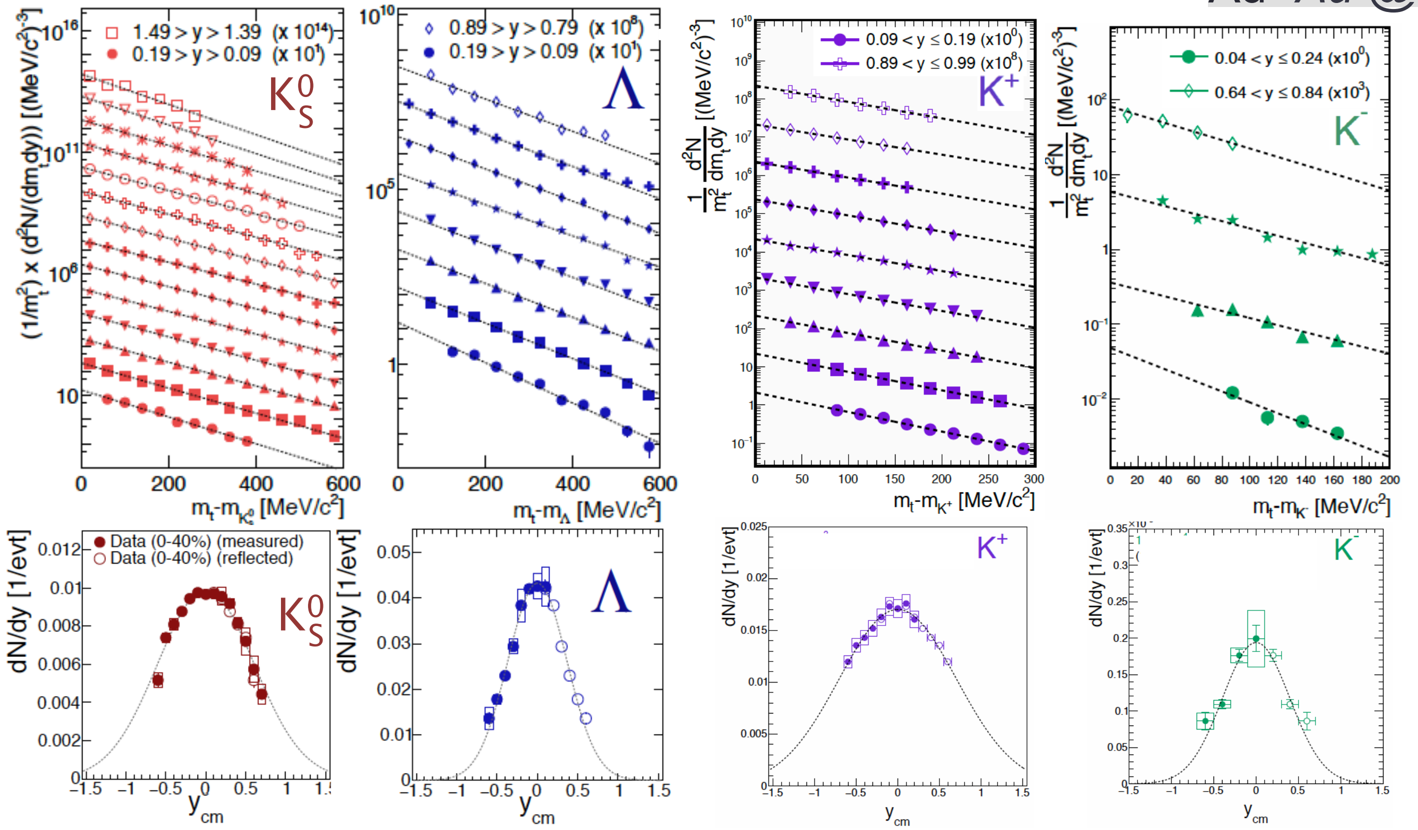


Evidence for increaseing average temperature as collisions go more central

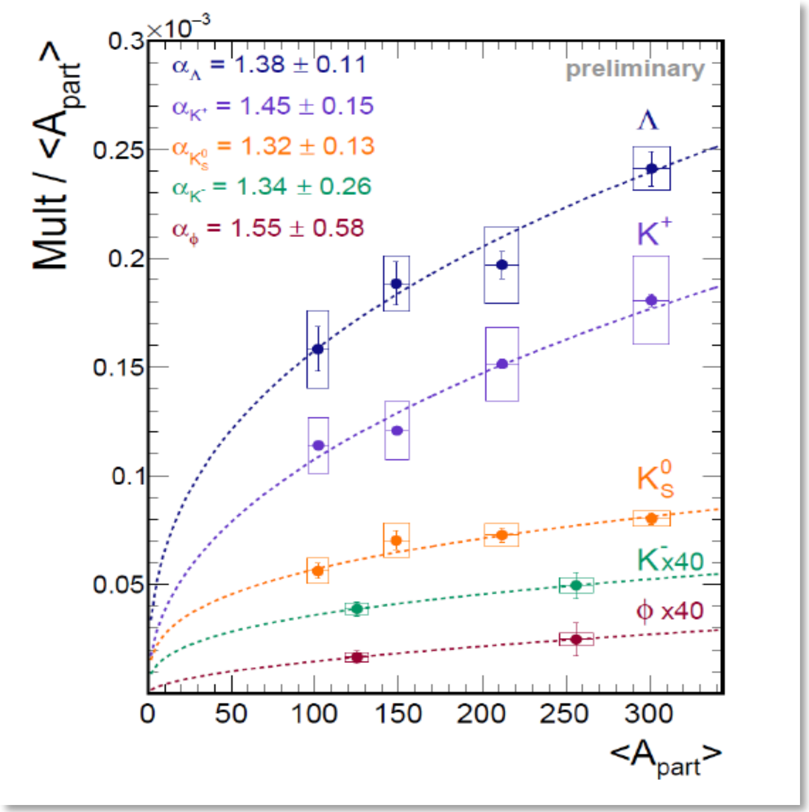
(...

Reconstructed Open Strangeness

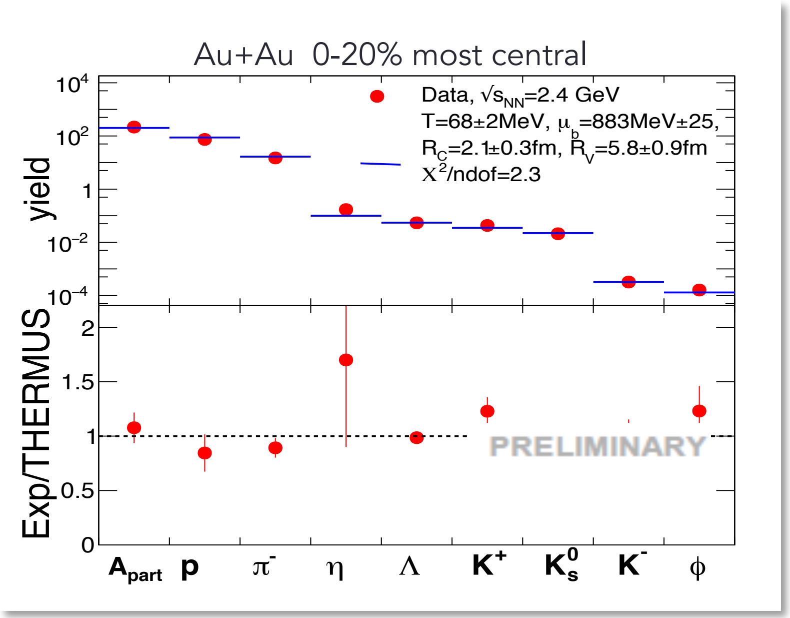
Au+Au @ $\sqrt{s}$=2.4 A GeV



Yields



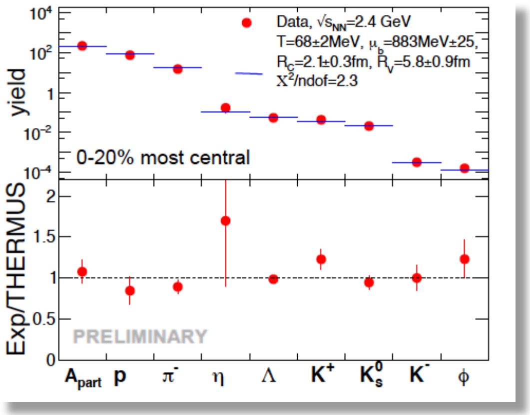
- All strange hadrons are produced below the free NN threshold: $\mathrm{K}^{+}\Lambda\ (-160\ MeV)$;$\mathrm{K}^{+}\mathrm{K}^{-}\ (-470\ MeV)$
- Canonical suppression applied in THERMUS (R_c), φ not affected.



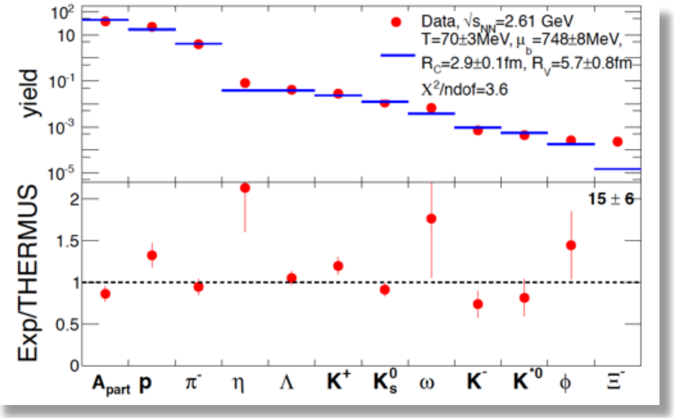
Statistical Interpretation of HADES Yields

- Measured (4π) yields can be interpreted by using canonical suppression for open strangeness (R_c)
- Also for p+A
- Inclusion of “non-strange” ϕ meson drives the fit to somewhat higher $T/\ \mu_B$
- Double-strange hyperon **not** explained

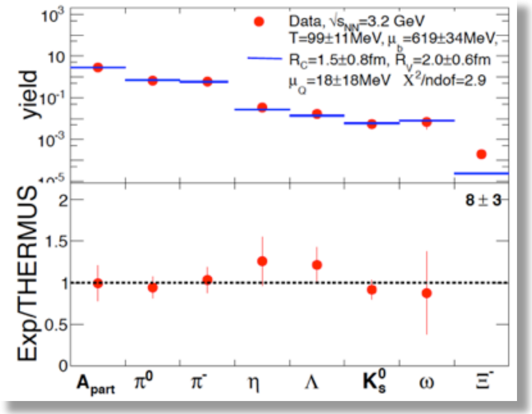
Au+Au $\sqrt{s_{NN}}$= 2.42 GeV



Ar+KCl $\sqrt{s_{NN}}$= 2.61 GeV

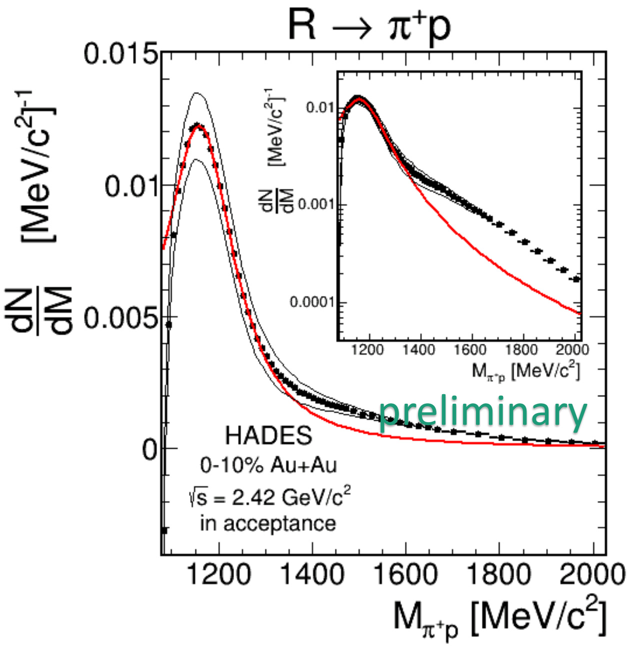


p+Nb $\sqrt{s_{NN}}$= 3.2 GeV



Baryonic resonances

- Resonance concentration accessible near freeze-out through e.g. $\pi^{-} p$ invariant mass.
- At freeze-out concentration of resonances changes only by decay.
- All pions in the final state stem from baryonic resonance decay.



Baryon resonance density in SHM:

$$R_{\Delta,N^*} = \rho_{\Delta} / \rho_{N} \sim 2 g_{\Delta,N^*} / g_{N} \; (m$$

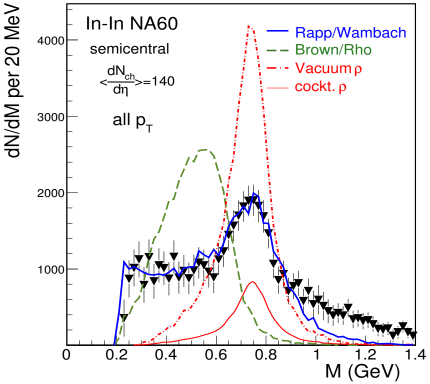
R_{Δ} = 0.03 – 0.15 for T = (50 – 100) MeV

$R_{N^*(1520)}$ = 4 10^{-5} – 1.2 10^{-2}

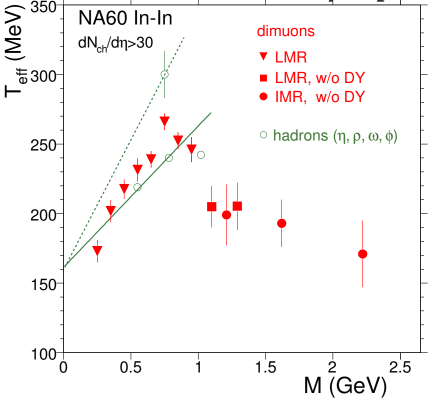
...)

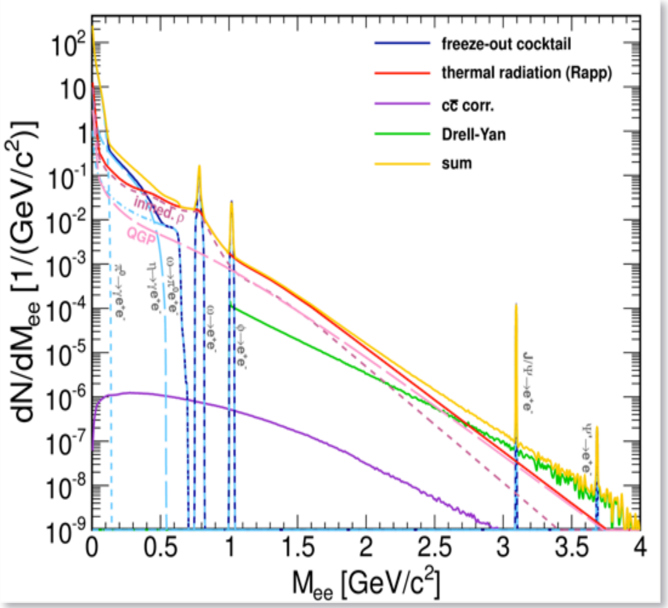
Dileptons as ...

Spectrometer



Barometer ($dN/dp_{\perp}$)

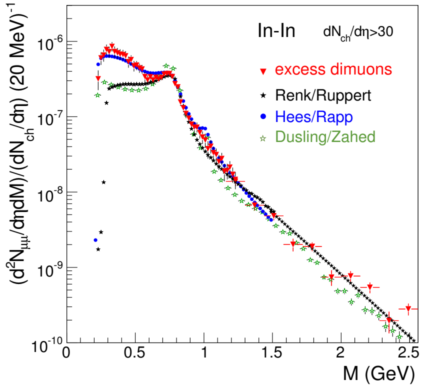




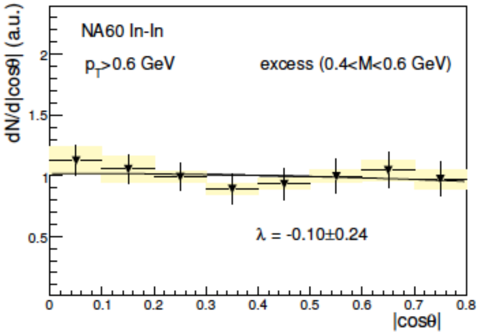
All data from NA60

... of the fireball

Thermometer



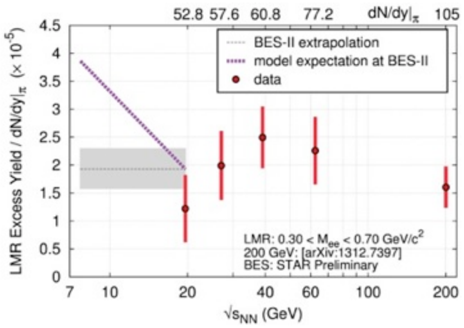
Polarimeter

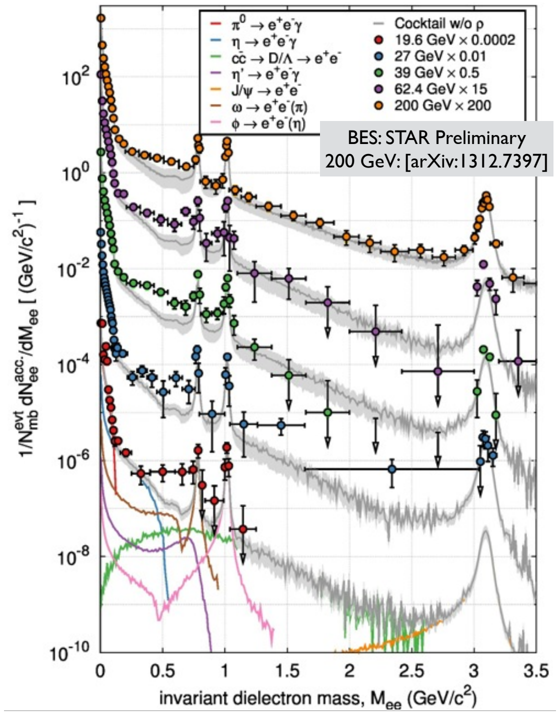


Rapp, Hees Phys.Lett. B753 (2016) 586-590 | Speranza, Jaiswal, Friman Phys.Lett. B782 (2018) 395-400

Excitation Functions

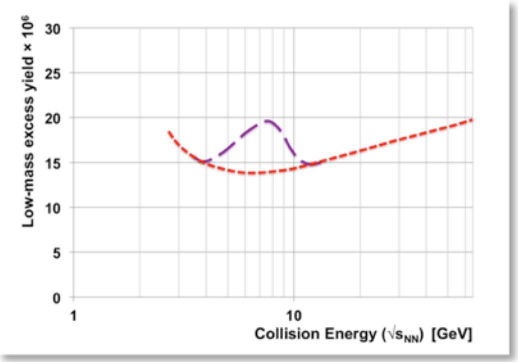
Patrick Huck, QM2014



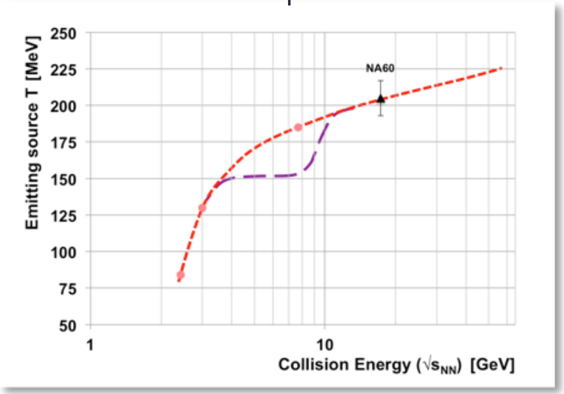


All data from STAR (preliminary)

Ecess yield



Mean temperature



Conjecture (very suggestive) for the case of a 1st order phase transition ☛

Conclusion

- Low-mass dileptons offer a complementary approach to properties of matter under extreme conditions by means of heavy-ion collisions.
- Effective fireball temperature accessible nearly model independent from invariant mass distribution of the excess radiation.
- Other properties (densities, lifetime) have some model dependence:
  - Emissivity currently based on diagrammatic model calculation (very successful though). Other approaches are followed up (FRG, Dyson-Schwinger, lQCD for net-baryon free matter).
  - Fireball evolution uncertain.
- If emissivity can be further scrutinized (elementary collisions, systematics), it can serve as standard candle for the fireball evolution.
- A combined fit to multi-differential observables (invariant mass, transverse momentum "ellipticity") might reveal the trajectory in the QCD phase diagram nearly model independent in future.

THANK YOU

The HADES collaboration